



Calhoun: The NPS Institutional Archive
DSpace Repository

Theses and Dissertations

1. Thesis and Dissertation Collection, all items

1946-09

Schlieren observation of supersonic discharge

Perry, Ellis L.; Renshaw, Loy W. A.; Perry, Ellis L.;
Renshaw, Loy W. A.

Massachusetts Institute of Technology

<http://hdl.handle.net/10945/6534>

This publication is a work of the U.S. Government as defined in Title 17, United States Code, Section 101. Copyright protection is not available for this work in the United States.

Downloaded from NPS Archive: Calhoun



Calhoun is the Naval Postgraduate School's public access digital repository for research materials and institutional publications created by the NPS community. Calhoun is named for Professor of Mathematics Guy K. Calhoun, NPS's first appointed -- and published -- scholarly author.

Dudley Knox Library / Naval Postgraduate School
411 Dyer Road / 1 University Circle
Monterey, California USA 93943

<http://www.nps.edu/library>

SCHLIEREN OBSERVATION OF
SUPERSONIC DISCHARGE

—•••—
E. L. PERRY,
L. W. A. RENSHAW

Library
U. S. Naval Postgraduate School
Monterey, California

Mont 211

8854

COPY FOR HEAD OF POSTGRADUATE SCHOOL

Library
U. S. Naval Postgraduate School
Annapolis, Md.

MASSACHUSETTS INSTITUTE OF TECHNOLOGY
Department of Mechanical Engineering
Cambridge 39, Mass., U.S.A.

Room 1-202

September 24, 1946

Captain W. H. Buracker
Room 5-233
Massachusetts Institute of Technology
Cambridge 39, Massachusetts

Thesis Work of LT E. L. PERRY, USCG ←
LT L. W. A. RENSHAW, USCG
LCDR W. W. SIMONS, USN
LCDR J. S. BOWEN, USN

Dear Captain Buracker:

The thesis by Lieutenants E. L. Perry and L. W. A. Renshaw entitled "Schlieren Observation of Supersonic Discharge" presents pressure measurements and Schlieren photographs of supersonic streams discharging into an exhaust space under various conditions. The photographs show interesting detail which in general corresponds to analytical results. The most significant observation was a comparison of two supersonic streams alike in average conditions but differing in thickness of the boundary layer. The effect of boundary-layer thickness on the nature of the shock pattern is shown clearly.

The thesis by Lt. Comdr^o W. W. Simons and J. S. Bowen entitled "Investigation of the Condensation Shock in Air by Use of the Schlieren Method" presents pressure measurements and Schlieren photographs of the shock patterns when water vapor in air condenses to form a fog of liquid or solid particles. It has extended our knowledge of the conditions which control condensation and of the condensation shock which accompanies it.

From either of these theses a paper could be prepared which would be published in one of the journals of the professional societies.

Yours truly,

/s/ Joseph H. Keenan

Joseph H. Keenan

1000
1057
SCHLITEN OBSERVATION

OF

SUPERSONIC DISCHARGE

BY

Lieut. E. L. Perry
B.S., U.S.C.G. Academy
1941

and

Lieut L.W.A. Renshaw
B.S., U.S.C.G. Academy
1941

Submitted in partial fulfillment of the
requirements for the degree of
Master of Science
at the
Massachusetts Institute of Technology
1946

Must
P34

add to [Internet Library of Theology](#)

05/06/150 7:20 3rd Floor

Department of Psychology, University of Toronto

© 2004 The Authors
Journal compilation © 2004 Blackwell Publishing Ltd

to, believe me

1892

MASSACHUSETTS INSTITUTE OF TECHNOLOGY
77 Massachusetts Avenue
Cambridge, Massachusetts

September 15, 1946

Professor Joseph S. Newell
Secretary of the Faculty
Massachusetts Institute of Technology
77 Massachusetts Avenue
Cambridge, Massachusetts

Dear Professor Newell:

Herewith we submit our thesis entitled "Schlieren
Observation of Supersonic Discharge" in partial fulfillment of the
requirements for the Degree of Master of Science in Naval
Construction and Engineering at the Massachusetts Institute of
Technology.

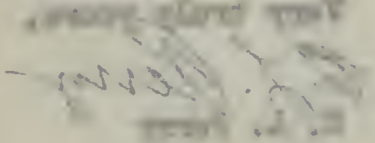
RESEARCH INSTITUTE OF TECHNOLOGY
77 Massachusetts Avenue
Cambridge, Massachusetts

September 12, 1944

Professor Joseph E. Smith
Secretary of the Faculty
Massachusetts Institute of Technology
77 Massachusetts Avenue
Cambridge, Massachusetts

Dear Professor Smith:

I am writing to you in regard to the
question of your possible election to the
position of the Director of the Institute of
Technology and Engineering of the Massachusetts Institute of
Technology.

Very truly yours,

J. W. A. Jackson

ACKNOWLEDGEMENT

With pleasure we acknowledge the help given us by Professor Joseph H. Keenan and Professor E. P. Neumann of the Mechanical Engineering Department. Thanks are also due to Dr. Joseph Kaye and Mr. Ferdinand Lustwerk. Mr. Lustwerk rendered invaluable assistance in developing laboratory equipment and technique.

Professor Joseph H. Keenan suggested the thesis topic.

TABLE OF CONTENTS

	Page
I. Summary	1
II. Introduction	3
III. Procedure	4
IV. Results and Discussion of Results	6
V. Conclusions and Recommendations	23
VI. Appendix	24
A. Details of Procedure	25
B. Experimental Data	28
C. Location of Original Data	37
D. Bibliography	38

CONTENTS

Page

I	1
II	11
III	121
IV	17
V	27
VI	37
VII	47
VIII	57
IX	67
X	77
XI	87
XII	97

SUMMARY

This work was undertaken to observe the effect on the discharge phenomenon of a supersonic air stream due to a change in Mach Number and a change of boundary layer thickness at constant Mach Number. Two (2) two-dimensional nozzles were designed using the Prandtl Theory, one having a Mach Number of 1.85 and the other a Mach Number of 1.39. A third nozzle was formed by adding a length of straight tube to the profile of the first nozzle to bring the Mach Number down to 1.39 by friction. All nozzles were designed for the same flow per unit area in the exit.

A comparison of the discharge of the first and second nozzles should show the effect of Mach Number, whereas a comparison of the second and third nozzles should show the effect of boundary layer thickness. The comparisons were made by Schlieren photographs and pressure measurements by mercury manometers at a point one eighth ($1/8$) inch from the exit of the nozzle and in the discharge chamber. It is noted that the nozzles were mounted perpendicular to the knife edge in the apparatus.

The results of the first comparison are not too conclusive. Further study in this line is recommended. The second comparison shows that a thick boundary layer cannot support anything resembling a transverse shock whereas a thin boundary layer will. Pressure measurement revealed that even in the thinnest boundary layers we were able to obtain there was no abrupt rise in pressure in the exit of the nozzles - like that expected in frictionless flow - as the exhaust pressure was increased. It is pointed out that the pressure was measured at the wall at a point one eighth ($1/8$) inch from exit. The photographs show that as the exhaust pressure is increased, the

oblique shock tends to creep back from the exit. This is shown in Figures VIII, IX and X. The gradual rise in exit pressure shown by our measurements may be due to this creeping back of the oblique shock over the pressure tap. Figure I shows that there were slight discontinuities in the pressure curve for the high Mach Number discharge. The photographs in this region - Figures XI, XII and XIII - depict this instability in the flow.

It is recommended that further work of this nature be carried out with the nozzles mounted parallel to the knife edge of the Schlieren apparatus in order to observe more precisely the contribution of the boundary layer to the discharge phenomena.

...the ... of the ...
 ...the ... of the ...
 ...the ... of the ...
 ...the ... of the ...
 ...the ... of the ...
 ...the ... of the ...
 ...the ... of the ...

...the ... of the ...
 ...the ... of the ...
 ...the ... of the ...
 ...the ... of the ...
 ...the ... of the ...
 ...the ... of the ...
 ...the ... of the ...

...the ... of the ...
 ...the ... of the ...
 ...the ... of the ...
 ...the ... of the ...
 ...the ... of the ...
 ...the ... of the ...
 ...the ... of the ...

INTRODUCTION

The academic interest in the flow of fluids at supersonic velocities has recently become of practical importance due to the development of gas turbines etc. The theory of the manner in which a supersonic stream from a nozzle or tube adjusts itself to the pressure in the exhaust space is well developed.

This work proposes to investigate and observe by Schlieren methods of photography the manner in which such adjustments are accomplished and the effects of different Mach Numbers and different boundary layer thicknesses on the phenomena.

INTRODUCTION

The analysis of the data of the first experiment is presented in the first chapter. The results of the second experiment are presented in the second chapter. The results of the third experiment are presented in the third chapter. The results of the fourth experiment are presented in the fourth chapter. The results of the fifth experiment are presented in the fifth chapter. The results of the sixth experiment are presented in the sixth chapter. The results of the seventh experiment are presented in the seventh chapter. The results of the eighth experiment are presented in the eighth chapter. The results of the ninth experiment are presented in the ninth chapter. The results of the tenth experiment are presented in the tenth chapter.

PROCEDURE

Three (3) two-dimensional nozzles were designed. These were fitted with plane glass sides so that the flow in the exit and discharge chamber could be observed by a Schlieren apparatus. The first of these nozzles (designated Nozzle #1 and shown in Figure XXXVI, Appendix B) was designed to have as little boundary layer as possible and a Mach Number of 1.85. The second nozzle (designated Nozzle #2 and shown in Figure XXXVII, Appendix B) was designed for the same flow per unit area at the exit and a Mach Number of 1.39. A comparison of these two nozzles should show some effect of Mach Number change on the discharge. The boundary layer should be small in each since they are very short.

To compare the discharge at the same Mach Number and different boundary layer thicknesses a straight portion was added to the contour of Nozzle #1 to reduce the Mach Number by friction to the same value as that of Nozzle #2 - (1.39). It was anticipated that some adjustment of the length of the straight portion would have to be made to bring the Mach Number to 1.39. This was later found to be the case.

The laboratory procedure consisted of mounting the nozzles in the Schlieren apparatus and taking suction with a steam jet air ejector. Air at room temperature and atmospheric pressure was used as supply to all the nozzles. It is noted that in order to maintain the same flow per unit area for Nozzle #2, a specially designed reducing fitting shown in Figure XXXIX was used to reduce the inlet pressure to two thirds ($2/3$) atmosphere.

Starting with the lowest pressure we could obtain in the

discharge the exhaust pressure was allowed to increase in steps until the pressure shocks were seen to move back into the nozzle. Readings of the exhaust pressure and the pressure one eighth ($1/8$) inch upstream from the exit plane were made by mercury manometer and recorded. Photographs were made at each step using the Edgerton Flash Unit described in Reference (1). Graphs of exit pressure vs exhaust pressure were plotted,

RESULTS AND DISCUSSION OF RESULTS

The results of the experiment are shown in Figures I to XXXV.

A comparison of Figure I and Figure II would indicate that a phenomenon more closely approaching a theoretical transverse shock is found in flow at higher Mach Number. The break in the pressure curve for Nozzle #1 (Mach Number 1.85) at an exhaust pressure of about 240 mm Hg. is much more pronounced than for any in the curve for Nozzle #2 (Mach Number 1.39). Examination of Figures X, XI and XII shows some instability of the discharge at the instant the shock occurs at the exit of the nozzle for the higher Mach Number. No such instability was observed at the lower Mach Number (1.39). Figures XXV, XXVI and XXVII show, however, what appears to be a transverse shock at the lower Mach Number. It is believed that the comparatively smooth pressure curve for Nozzle #2 is caused by the length of the shock. Apparently the flow separates from the tube wall near the exit and the shock passes smoothly up the nozzle as the exhaust pressure increases ; whereas at the higher Mach Number the shock is much shorter and the flow less stable. We were unable to stop the shock in the exit of this nozzle.

Under all conditions the pressure in the stream adjusted itself to a lower exhaust pressure by the expansion wedges expected from the Meyer Theory of flow around a corner. This is shown in Figures IV, XXII and XXVIII. Small and moderate adjustments to a higher exhaust pressure were made in all cases by the medium of an oblique shock. There was a tendency for the oblique shock to creep back into the nozzle as the exhaust pressure increased. It is observed that this tendency became very pronounced in the case

of the thick boundary layer. It is possible that the gradual rise in the observed exit pressure as the exhaust pressure is increased is due to the oblique shock creeping back over the pressure tap which is located one eighth ($1/8$) inch from the exit. In that event the observed pressures are probably not the true pressures in the center of the stream at exit.

A comparison of Figure II and III show a marked similarity in the pressure relations of the two discharges at the same Mach Number (1.39) but different boundary layer thicknesses. It is noted that the curve for Nozzle #3 with a thick boundary layer is displaced to the right by about 15 mm Hg. on the exhaust pressure scale.

The mechanism by which the pressure in the stream adjusts itself to a considerably higher exhaust pressure is shown in Figures XXXII to XXXV and Figures XXIV to XXVII to be somewhat different in these two cases. In the case of the thick boundary layer Figures XXXII to XXXV show that nothing resembling a transverse shock occurs. Instead, the boundary layer, which is subsonic, appears to increase in area while the supersonic stream decreases in area; thus the pressure rises to that of the exhaust chamber. The oblique shocks which are set up and reflect downstream appear to originate at the point where contraction of the supersonic stream begins. It is possible that this apparent enlargement of the boundary layer cross section is actually a flow separation from the wall. The observation that this phenomenon occurs only in the case with thick boundary layer supports the former assumption, however.

It is recommended that further work on this point be carried

out with the nozzle mounted parallel to the knife edge of the Schlieren apparatus so that a better idea of what is going on in the boundary layer may be obtained.

In the case of the thin boundary layer no such separation or enlargement is observed. What appears to be a transverse shock with perhaps a little separation is shown in Figures XXiv to XXVII.

Investigation of the effect of Mach Number on the discharge with thick boundary layer is also recommended. It would be interesting to make observations at a Mach Number of 1.39 and with a boundary layer intermediate in thickness between the two cases used in this work.

As is noted in Appendix A the length of straight tube necessary to reduce the Mach Number of Nozzle 1 to that of Nozzle 2 was calculated to be 10.35 inches. Actual experiment revealed that this value should be 6.02 inches and the length was accordingly reduced to that value.

Due to extremely low temperatures of the stream it was practically impossible to prevent the condensation of moisture on the outside surfaces of the glass plates. This resulted in smudges similar to those shown in Figures IX, X, XXVIII and XXX.

and that the results recorded parallel in the same way at the
different experiments in that a further drop of water is added to the
the boundary layer may be obtained.

In the case of the thin boundary layer in the transition zone
adjustment is observed. That appears to be a transition from the
boundary a little expansion is shown in Figure III to III.

Investigation of the effect of water vapor on the discharge at
thin boundary layer is also recommended. It would be interesting to
also observations of a thin layer of 1.5 and with a boundary layer
transition in thickness between the two cases next to each other.

As it is found in Figure A the length of electric discharge
is reduced the same water vapor in Figure B to that of Figure C and calculated
to be 10.32 inches. Actual experiment revealed that this value should
be 6.00 inches and the length was accordingly reduced to that value.

It is necessary for comparison of the results it is
particularly desirable to present the comparison of values of the
surface surface of the glass plates. This is noted in Figure
relative to those shown in Figures I, II, III and IV.

FIGURE I

NOZZLE 1

P_e = Exhaust Pressure

P_g = Pressure in Exit

Nozzle Inlet Pressure 761.2 mm Hg.

Inlet Temp. 85° F.

July 19, 1946

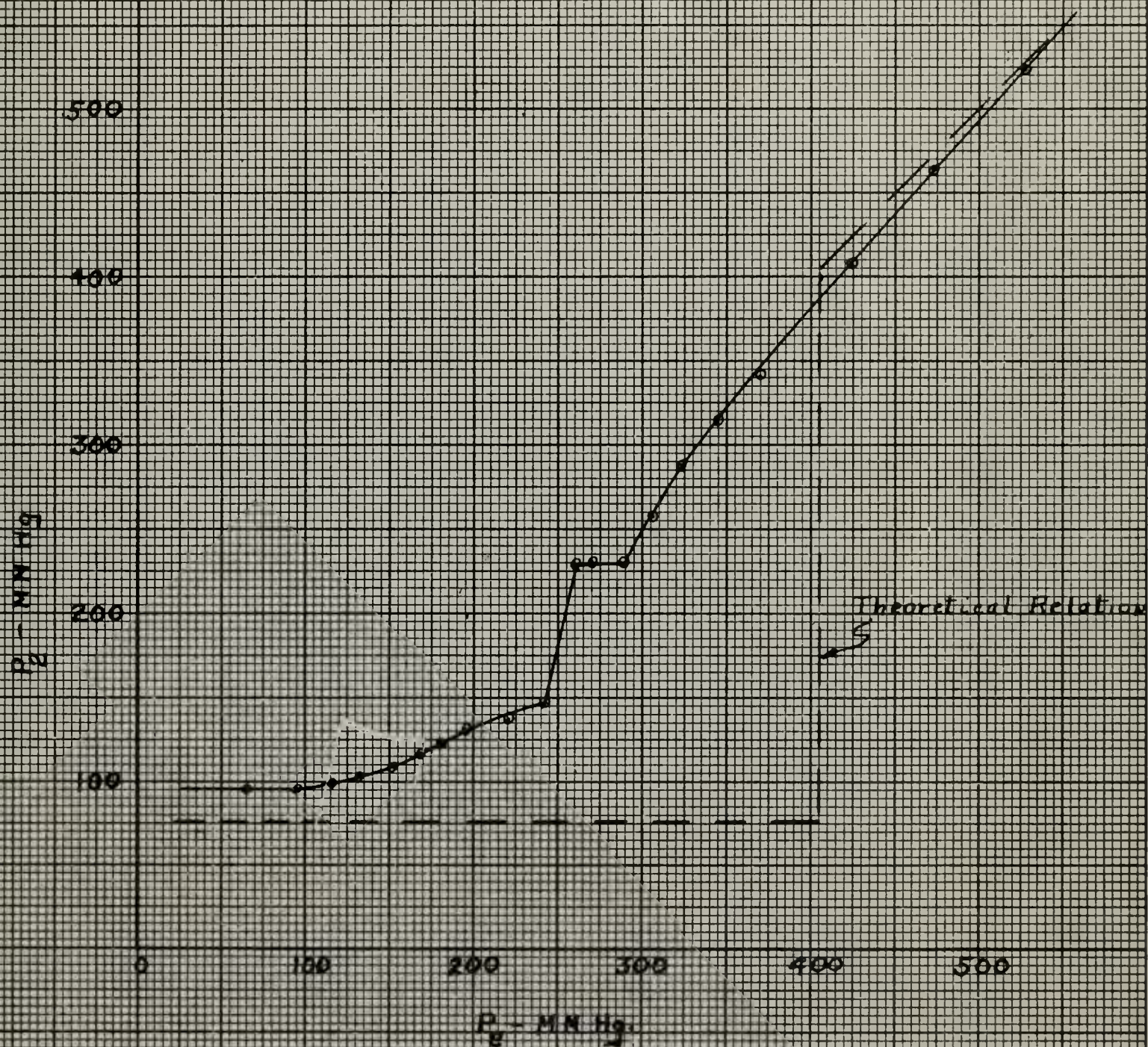


FIGURE II

NOZZLE 2

P_e = EXHAUST PRESSURE

P_2 = PRESSURE IN EXIT.

NOZZLE INLET PRESSURE 502 mm Hg.

Inlet Temp 85°F

July 15, 1946

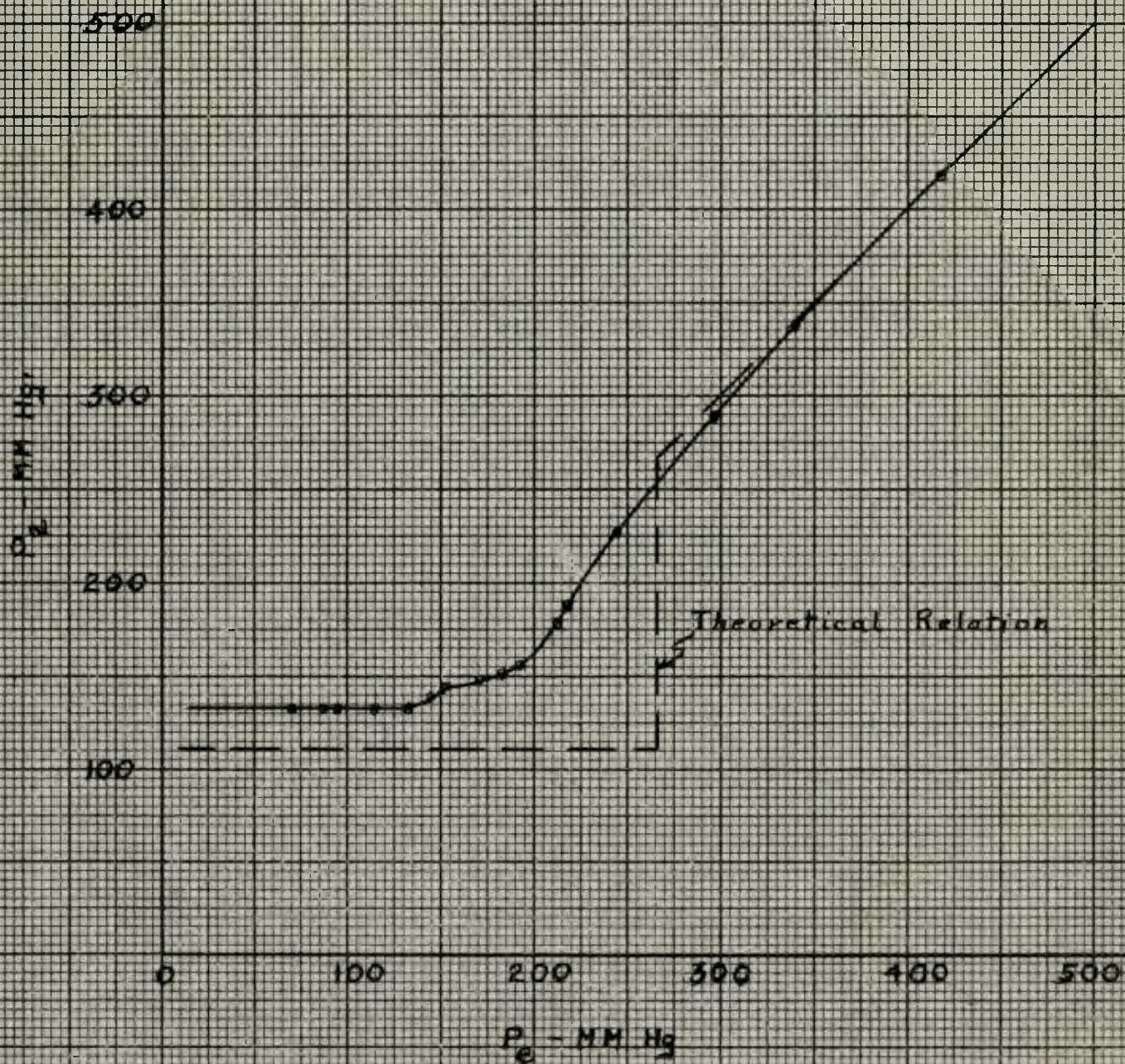


FIGURE III

NOZZLE 3

P_e = Exhaust Pressure mm Hg

P_g = Pressure in Exit "

Nozzle Inlet Pressure 764.4 mm Hg

Tube Inlet Pressure 93.4 "

July 22, 1946

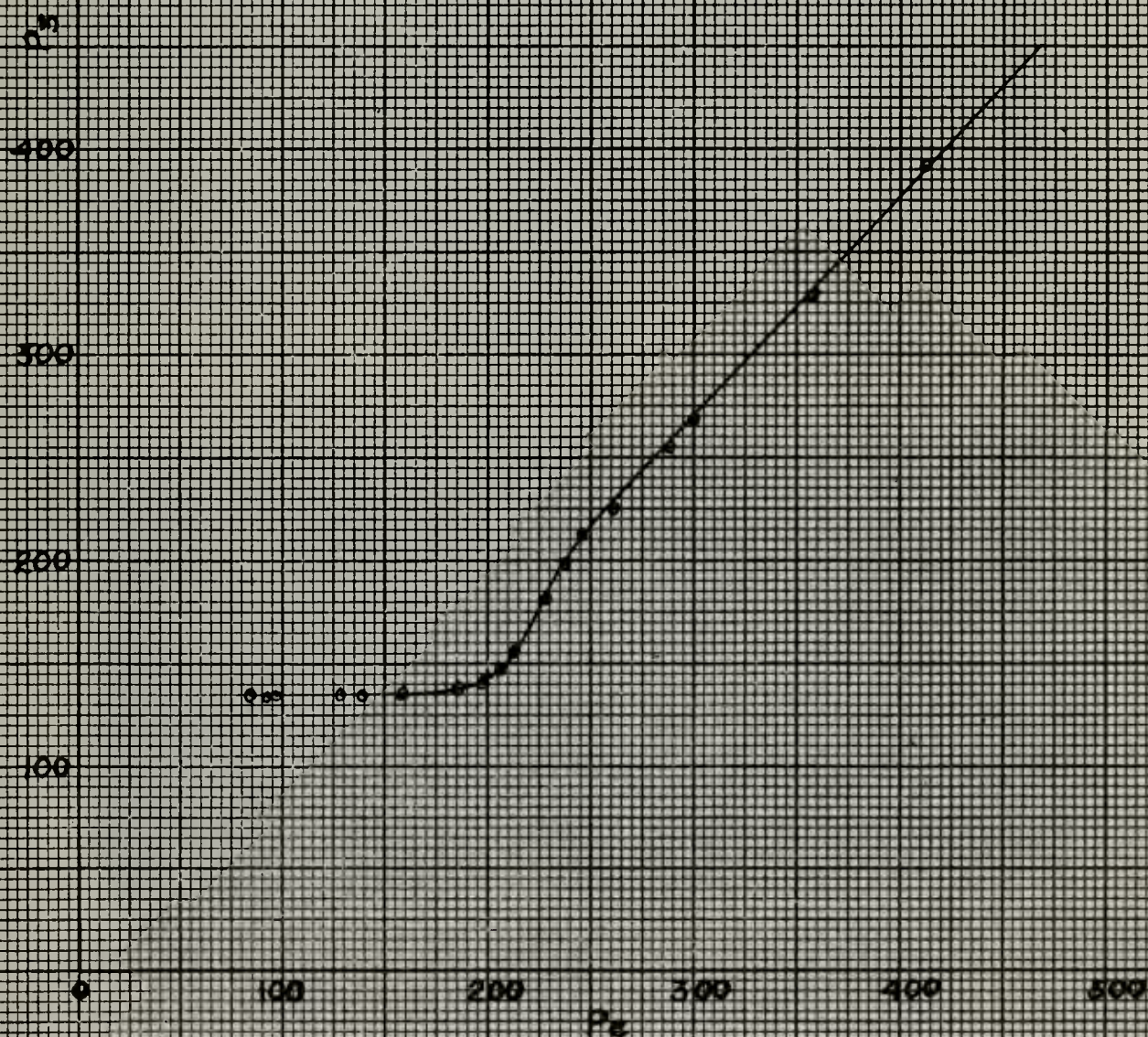




FIGURE IV

Nozzle #1

$P_0 = 74$
 $P_2 = 95$

Flash



FIGURE V

Nozzle #1

$P_0 = 95$
 $P_2 = 95$

Flash



FIGURE VI

Nozzle #1

$P_0 = 111$
 $P_2 = 99$

Flash



FIGURE IV

Nozzle #1

$P_0 = 74$
 $P_2 = 95$

Flash



FIGURE V

Nozzle #1

$P_0 = 95$
 $P_2 = 95$

Flash



FIGURE VI

Nozzle #1

$P_0 = 111$
 $P_2 = 99$

Flash

17 4 5
 10 2 10
 10 2 10

17 4 5
 10 2 10
 10 2 10

17 4 5
 10 2 10
 10 2 10



FIGURE VII

Nozzle #1

P_0 - 139
 P_2 - 107

Flash



FIGURE VIII

Nozzle #1

P_0 - 171
 P_2 - 117

Flash



FIGURE IX

Nozzle #1

P_0 - 194
 P_2 - 131

Flash

1. The first part of the paper is devoted to a discussion of the general principles of the theory of the structure of the atom. It is shown that the structure of the atom is determined by the laws of quantum mechanics, and that the laws of quantum mechanics are in agreement with the experimental facts.

2. The second part of the paper is devoted to a discussion of the application of the theory of the structure of the atom to the study of the properties of the elements of the periodic system. It is shown that the theory of the structure of the atom is in agreement with the experimental facts.

3. The third part of the paper is devoted to a discussion of the application of the theory of the structure of the atom to the study of the properties of the compounds of the elements of the periodic system. It is shown that the theory of the structure of the atom is in agreement with the experimental facts.

4. The fourth part of the paper is devoted to a discussion of the application of the theory of the structure of the atom to the study of the properties of the solutions of the elements of the periodic system. It is shown that the theory of the structure of the atom is in agreement with the experimental facts.

5. The fifth part of the paper is devoted to a discussion of the application of the theory of the structure of the atom to the study of the properties of the alloys of the elements of the periodic system. It is shown that the theory of the structure of the atom is in agreement with the experimental facts.

6. The sixth part of the paper is devoted to a discussion of the application of the theory of the structure of the atom to the study of the properties of the compounds of the elements of the periodic system. It is shown that the theory of the structure of the atom is in agreement with the experimental facts.



FIGURE X Nozzle #1 $P_0 - 212$ Flash
 $P_2^* - 140$



FIGURE XI Nozzle #1 $P_0 - 246$ Flash
 $P_2 - 169$



FIGURE XII Nozzle #1 $P_0 - 271$ Flash
 $P_2 - 230$

1871 1872 1873 1874

1875 1876 1877 1878

1879 1880 1881 1882



FIGURE XIII

Nozzle #1

P_0 - 123
 P_2 - 288

Flash



FIGURE XIV

Nozzle #1

P_0 - 92
 P_2 - 95

1/80 Sec.



FIGURE XV

Nozzle #2

P_0 - 73.59
 P_2 - 133.5
 P_1 - 503.5

1/80 Sec.

0
2
3
4
5



FIGURE XVI

Nozzle #2

P_e - 96.5
 P_2 - 133.5
 P_1 - 508.5

1/80 Sec.



FIGURE XVII

Nozzle #2

P_e - 132
 P_2 - 133
 P_1 - 504

1/80 Sec.

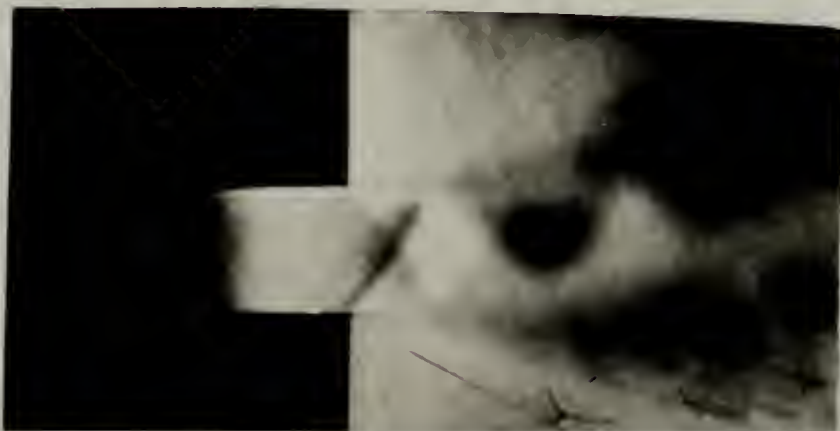


FIGURE XVIII

Nozzle #2

P_e - 144
 P_2 - 138
 P_1 - 502

1/80 Sec.

1000	1000	1000	1000
1000	1000	1000	1000
1000	1000	1000	1000

1000	1000	1000	1000
1000	1000	1000	1000
1000	1000	1000	1000

1000	1000	1000	1000
1000	1000	1000	1000
1000	1000	1000	1000



FIGURE XIX

Nozzle #2

P_0 - 192
 P_2 - 155
 P_1 - 504

1/80 Sec.

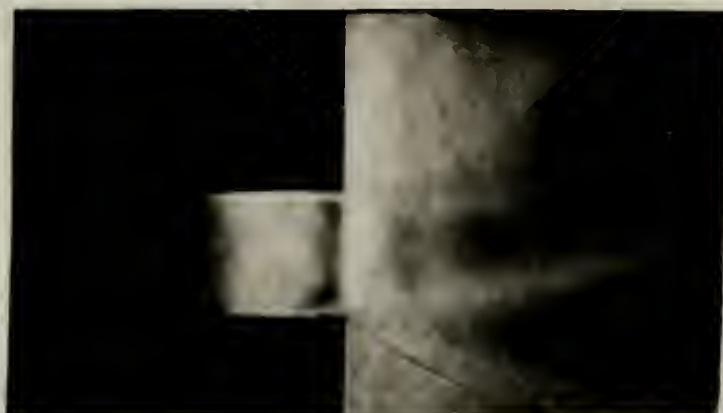


FIGURE XX

Nozzle #2

P_0 - 217
 P_2 - 187
 P_1 - 502

1/80 Sec.



FIGURE XXI

Nozzle #2

P_0 - 235
 P_2 - 217
 P_1 - 501

1/80 Sec.



FIGURE 1

Sample 1

100%
100%
100%

100% 100%



FIGURE 2

Sample 2

100%
100%
100%

100% 100%



FIGURE 3

Sample 3

100%
100%
100%

100% 100%

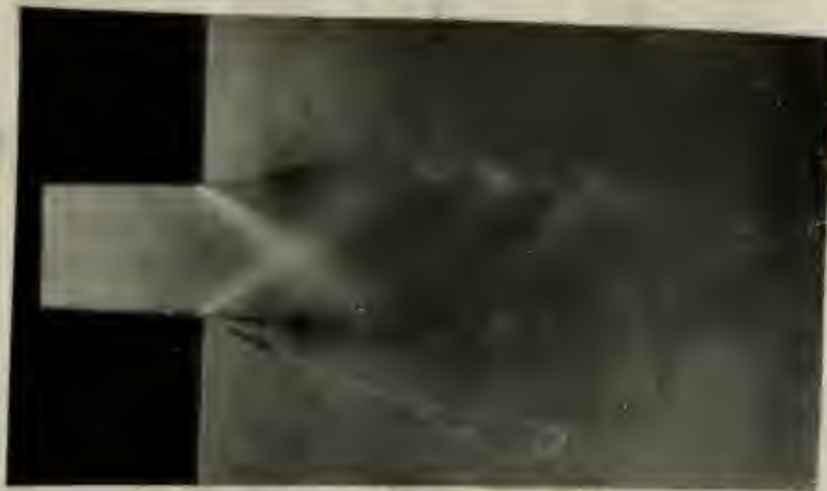


FIGURE XXII

Nozzle #2

P_e - 98
 P_2 - 130
 P_1 - 509

Flash



FIGURE XXIII

Nozzle #2

P_e - 131
 P_2 - 131
 P_1 - 508

Flash



FIGURE XXIV

Nozzle #2

P_e - 156
 P_2 - 145
 P_1 - 508

Flash



1895

1895
1896
1897
1898

1895

1895



1895

1895
1896
1897
1898

1895

1895



1895

1895
1896
1897
1898

1895

1895

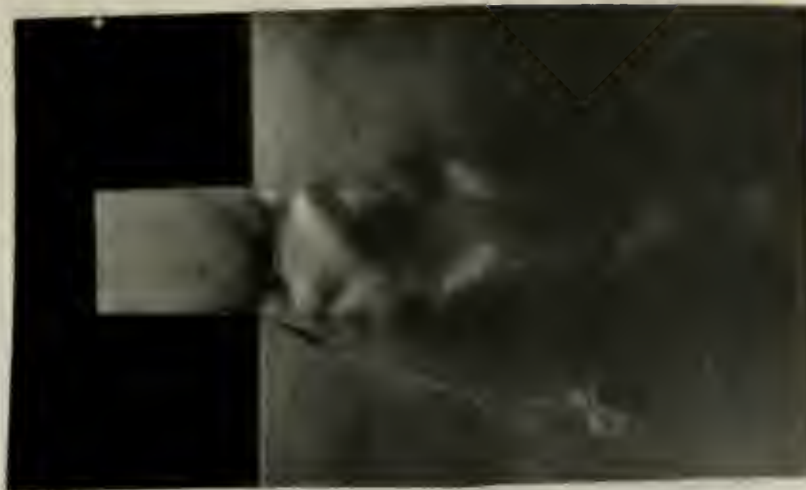


FIGURE XXV

Nozzle #2

P₀ - 186
P₂ - 148
P₁ - 506

Flash

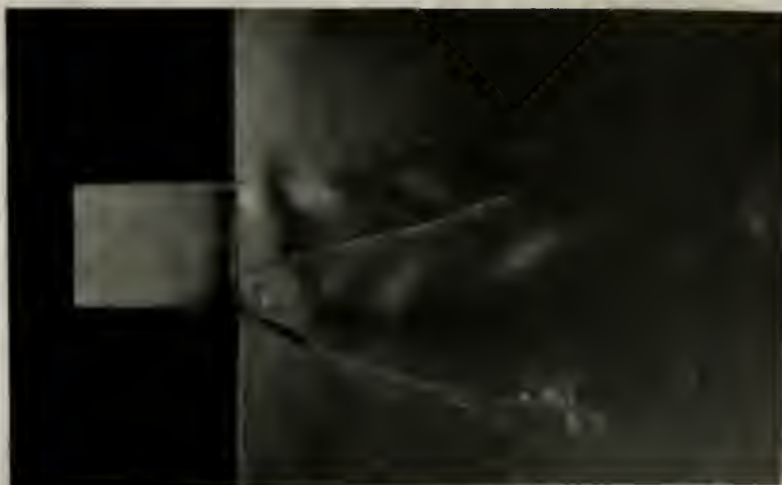


FIGURE XXVI

Nozzle #2

P₀ - 219
P₂ - 191
P₁ - 504

Flash



FIGURE XXVII

Nozzle #2

P₀ - 235
P₂ - 215
P₁ - 504

Flash



1711

1711
1712
1713

1714

1715



1716

1716
1717
1718

1719

1720



1721

1721
1722
1723

1724

1725



FIGURE XXVIII

Nozzle #3

P_0 - 80.4
 P_3 - 136.4

Flash



FIGURE XXIX

Nozzle #3

P_0 - 113.4
 P_3 - 136.4

Flash



FIGURE XXX

Nozzle #3

P_0 - 172.4
 P_3 - 136.4

Flash



Blank

1.00 - 1.00
1.00 - 1.00

1.00 - 1.00

1.00 - 1.00



Blank

1.00 - 1.00
1.00 - 1.00

1.00 - 1.00

1.00 - 1.00



Blank

1.00 - 1.00
1.00 - 1.00

1.00 - 1.00

1.00 - 1.00



FIGURE XXI

Nozzle #3

P_e - 197.3
 P_3 - 141.4

Flash



FIGURE XXXII

Nozzle #3

P_e - 213.4
 P_3 - 156.4

Flash



FIGURE XXXIII

Nozzle #3

P_e - 238.4
 P_3 - 198.4

Flash



FIGURE XXXIV

Nozzle #3

P_e - 261.4
 P_3 - 225.4

Flash

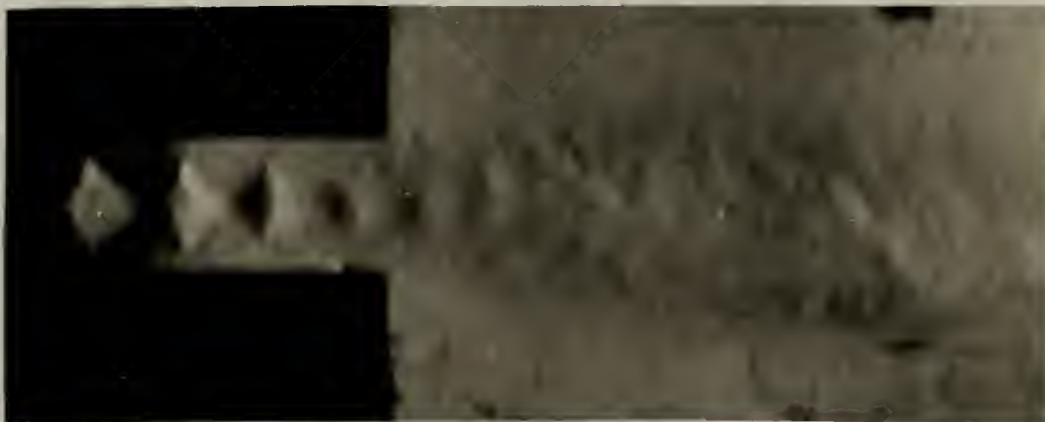


FIGURE XXXV

Nozzle #3

P_e - 300.4
 P_3 - 267.4

Flash

1. 100 - 4
 2. 100 - 4
 3. 100 - 4
 4. 100 - 4
 5. 100 - 4
 6. 100 - 4
 7. 100 - 4
 8. 100 - 4
 9. 100 - 4
 10. 100 - 4

1. 100 - 4
 2. 100 - 4
 3. 100 - 4
 4. 100 - 4
 5. 100 - 4
 6. 100 - 4
 7. 100 - 4
 8. 100 - 4
 9. 100 - 4
 10. 100 - 4

1. 100 - 4
 2. 100 - 4
 3. 100 - 4
 4. 100 - 4
 5. 100 - 4
 6. 100 - 4
 7. 100 - 4
 8. 100 - 4
 9. 100 - 4
 10. 100 - 4

1. 100 - 4
 2. 100 - 4
 3. 100 - 4
 4. 100 - 4
 5. 100 - 4
 6. 100 - 4
 7. 100 - 4
 8. 100 - 4
 9. 100 - 4
 10. 100 - 4

CONCLUSIONS AND RECOMMENDATIONS

1. Regardless of Mach Number, in supersonic flow the rise of pressure in the exit plane of a practical nozzle is not sudden (in accordance with the theoretical relation) but occurs slowly over a considerable range of exhaust chamber pressure.
2. With thick boundary layer the flow will not support anything resembling a transverse shock.
3. Thickness of boundary layer has the controlling influence on the mechanism by which a supersonic stream adjusts itself to the pressure in the exhaust chamber.
4. It is recommended that further work in this line be carried out with the nozzles mounted parallel to the knife edge of the Schlieren apparatus under the following conditions:
 - (a) Use nozzles #1 and #3 of Appendix B.
 - (b) Use a nozzle with a tube approximately three (3) inches long at a Mach Number of about 1.39 at exit.
 - (c) Use a nozzle with a tube approximately six (6) inches long at a Mach Number of about 1.85 at exit.
5. It is also recommended that investigations of the effect of flow per unit area at the same Mach Number upon the discharge phenomena be carried out.

1.

Comparison of the two, in general, the rise of pressure in the case of a practical device in use within its tolerance with the theoretical relation, but occurs slightly over a considerable range of values.
2.

With this pressure, the rise will not occur, and the resulting a pressure drop.
3.

Thickness of material layer and the resulting influence of the material by which a pressure is applied, adjust itself to the pressure in the system.
4.

It is recommended that further work in this line be carried out with the material mounted parallel to the edge of the specimen, and the following conditions:

 - (a) Two series of test of specimen 1.
 - (b) Two series with a thin specimen (1) and (2).
 - (c) Two series with a thick specimen of about 1.5 at 1.5.
 - (d) Two series with a thin specimen at 1.5.
 - (e) Two series with a thick specimen at 1.5.
5.

It is also recommended that investigation of the effect of the pressure on the rise of the material when the discharge pressure is applied.

APPENDIX

... of the ...
... of the ...
... of the ...
... of the ...

... of the ...
... of the ...

... of the ...
... of the ...
... of the ...
... of the ...

... of the ...
... of the ...

CHAPTER

... of the ...
... of the ...

... of the ...
... of the ...

... of the ...
... of the ...

... of the ...
... of the ...

APPENDIX A -- DETAILS OF PROCEDURE

Reference (3) illustrates that a good shockless nozzle may be designed by the use of the Prandtl Theory; therefore it was decided to use this method as the basis of the nozzle design. The nozzle design was merely a reproduction of the work of Reference (3) but using different area ratios. A theoretical pressure ratio of .10 was chosen for the basic nozzle (Figure XXIV, Appendix B) with an angle of divergence of $14^{\circ} 15'$. The theoretical Mach number at the exit of this nozzle is 2.152 based on $k = 1.400$. The area ratio is 1.9307. A velocity coefficient of .95 was assumed and the actual Mach number calculated to be 1.85 with a pressure ratio of .124.

It was desired to investigate the effect of Mach number with approximately constant boundary layer thickness on the discharge phenomena. To accomplish this a second nozzle (Figure XXV, Appendix B) was designed with an area ratio of 1.287. In order to maintain the same flow per unit area at the exit of the two nozzles the inlet pressure in this nozzle was reduced to two thirds ($2/3$) of an atmosphere by a specially designed adjustable fitting (Figure XXVI, Appendix B). With an assumed velocity coefficient of .95, r was calculated as .275 and the Mach number at exit as 1.39. In order to keep both nozzles the same length the angle of divergence was reduced to six (6) degrees. It was believed that any differences that might be caused by this change of angle of divergence would be less than those caused by a change in length which would affect the boundary layer.

In order to observe the effect of boundary layer thickness

Reference is made to the fact that a tunnel design is not designed by the use of the Tunnel Theory, therefore it was decided to use this method as the basis of the tunnel design. The tunnel design was made by a comparison of the work of Reference (1) and using different size ratios. A theoretical pressure ratio of 1.0 was chosen for the tunnel design (Figure VIII, Appendix B) with an angle of divergence of 14° . The theoretical flow number at the exit of this tunnel is 2.13, based on $n = 1.40$. The actual ratio is 1.9307. A velocity coefficient of 0.95 was assumed and the actual flow number calculated to be 1.68 with a pressure ratio of 1.24.

It was desired to investigate the effect of flow number with approximately constant boundary layer thickness on the divergence phenomenon. To accomplish this a second tunnel (Figure VIII, Appendix B) was designed with an angle ratio of 1.25. In order to maintain the same flow for all parts of the exit of the two tunnels the ratio of pressure in this tunnel was reduced to two thirds (2/3) of an atmosphere by a specially designed adjustable fitting (Figure VIII, Appendix B). With an assumed velocity coefficient of 0.95, it was calculated as 2.13 and the flow number at exit as 1.93. In order to keep both tunnels the same length the angle of divergence was reduced to 10° (Figure IX). It was believed that any differences that might be caused by this change of angle of divergence would be less than those caused by a change in length which would affect the boundary layer.

In order to observe the effect of boundary layer thickness

on the discharge phenomena for the same Mach number at exit, it was decided to add to the basic nozzle (Nozzle 1) a straight constant area section of such length as to reduce the Mach number of Nozzle #1 (1.85) to the Mach number of Nozzle #2 (1.39). To eliminate the possibility of shock formation at the junction of the nozzle and tube it was decided to fabricate another nozzle with the straight portion integral with the nozzle itself (Figure XXXVIII). By use of data obtained from Reference (6) the length of tube necessary was calculated to be 10.35 inches. This figure was regarded as highly approximate due to the use of a two dimensional tube instead of the circular section upon which the data of Reference (6) is based.

Provision was made for pressure measurement by mercury manometer at a point one eighth ($1/8$) inch from the nozzle or tube exit and in the discharge chamber of all nozzles by a .020 inch diameter hole in the steel contour.

All pictures were taken with the axis of the nozzle perpendicular to the knife edge of the Schlieren apparatus described adequately in Reference (1).

The pictures designated "Flash" were made by using the Edgerton Flash Unit also described in Reference (1). This gave an exposure time of approximately $.5 \times 10^{-6}$ seconds. A few pictures were taken using a steady light source and an exposure time of $1/80$ seconds, to show the difference in detail of pictures obtained by the use of the two different methods.

on the discharge phenomena for the same kind of wires as used, it was decided to use in the present work (Series I) a straight constant area section of such length as to remove the end effect of Series I (1.5) to the back surface of Series II (1.5). To eliminate the possibility of short circuiting on the junction of the wires and the it was decided to fabricate another series of wires with a straight section integral with the wire itself (Series II), of the same length as the Series I (1.5) and the length of the straight section was increased to be 10.0 inches. This figure was selected as being representative of the use of a few dimensions, the length of the straight section being which the data of Reference (2) is based.

Provision was made for pressure measurement by means of a manometer of a point one eighth (1/8) inch from the wire or tube end and in the straight section of all wires of a 1/8 inch diameter hole in the steel container.

All distances were taken with the axis of the wire perpendicular to the axis of the holder and the holder was held rigidly in Reference (1).

The pressure distribution along the wire was measured by using the Wheatstone bridge with the holder in Reference (1). This was an exposure time of approximately 2×10^{-6} seconds. A few distances were taken using a sharp light source and an exposure time of 1/80 seconds, so that the differences in detail of pressure obtained by the use of the two different methods.

APPENDIX B---EXPERIMENTAL DATA

TABLE I

PRESSURE READINGS, NOZZLE I

19 JULY, 1946

P_e = Exhaust Chamber Pressure, mm. Hg.

P_2 = Pressure in Exit of Nozzle, mm. Hg.

P_a = Nozzle Inlet Pressure, Atmospheric

T_1 = Inlet Temperature, Degrees F.

P_e	P_2	P_a	T_1
74	95	761.2	85
95	95		
116	99		
133	104		
153	109		
169	116		
181	122		
196	131		
220	136		
241	197		
260	228		
287	230		
324	289		
370	341		
424	407		
473	464		
527	520		

STANDARD GRADE

TABLE I

1912, 1913, 1914

STANDARD GRADE, TABLE I

1 = Standard Grade, 1912, 1913, 1914

2 = Standard in 1912 of 1913, 1914

3 = Standard in 1913 of 1914, 1915

4 = Standard in 1914 of 1915, 1916

1	2	3	4
74	75	76	77
78	79	80	81
82	83	84	85
86	87	88	89
90	91	92	93
94	95	96	97
98	99	100	101
102	103	104	105
106	107	108	109
110	111	112	113
114	115	116	117
118	119	120	121
122	123	124	125
126	127	128	129
130	131	132	133
134	135	136	137
138	139	140	141
142	143	144	145
146	147	148	149
150	151	152	153
154	155	156	157
158	159	160	161
162	163	164	165
166	167	168	169
170	171	172	173
174	175	176	177
178	179	180	181
182	183	184	185
186	187	188	189
190	191	192	193
194	195	196	197
198	199	200	201

TABLE II

PRESSURE READINGS, NOZZLE # 2

13 JULY, 1946

P_e = Exhaust Chamber Pressure, mm. Hg.

P_2 = Pressure in Exit of Nozzle, mm. Hg.

P_1 = Nozzle Inlet Pressure, mm. Hg.

P_a = Atmospheric Pressure, mm. Hg.

T_1 = Nozzle Inlet Temperature, Degrees F.

<u>P_e</u>	<u>P_2</u>	<u>P_1</u>	<u>P_a</u>	<u>T_1</u>
71	133	502	761.5	85
86	133	502		
94	133	502		
113	133	502		
131	133	502		
144	138	502		
151	143	502		
171	146	502		
183	150	502		
192	155	502		
211	178	502		
217	188	502		
244	227	502		
296	288	502		
340	338	502		
418	417	502		

TABLE III

PRESSURE READINGS, NOZZLE #3

22 JULY, 1946

 P_e = Exhaust Chamber Pressure, mm. Hg. P_3 = Pressure at Exit of Tube, mm. Hg. P_2 = Pressure at Tube Inlet (Nozzle Exit), mm. Hg. P_a = Nozzle Inlet Pressure, Atmospheric T_1 = Inlet Temperature, Degrees F.

P_e	P_3	P_2	P_a	T_1
80.4	135.4	93.4	764.4	85
97	135			
113	135			
129	135			
140	135			
158	135			
185	137			
197	141			
206	148			
213	156			
228	181			
238	198			
246	213			
261	225			
288	255			
300	267			
358	329			

1. The first group of people who are interested in the study of the history of the United States are the people who are interested in the history of the United States.

U. S. DEPARTMENT OF THE INTERIOR

... (1980) ...

3. 2. 1964

1. *Thymus* 2. *Thymus* 3. *Thymus* 4. *Thymus* 5. *Thymus* 6. *Thymus* 7. *Thymus* 8. *Thymus* 9. *Thymus* 10. *Thymus* 11. *Thymus* 12. *Thymus* 13. *Thymus* 14. *Thymus* 15. *Thymus* 16. *Thymus* 17. *Thymus* 18. *Thymus* 19. *Thymus* 20. *Thymus* 21. *Thymus* 22. *Thymus* 23. *Thymus* 24. *Thymus* 25. *Thymus* 26. *Thymus* 27. *Thymus* 28. *Thymus* 29. *Thymus* 30. *Thymus* 31. *Thymus* 32. *Thymus* 33. *Thymus* 34. *Thymus* 35. *Thymus* 36. *Thymus* 37. *Thymus* 38. *Thymus* 39. *Thymus* 40. *Thymus* 41. *Thymus* 42. *Thymus* 43. *Thymus* 44. *Thymus* 45. *Thymus* 46. *Thymus* 47. *Thymus* 48. *Thymus* 49. *Thymus* 50. *Thymus* 51. *Thymus* 52. *Thymus* 53. *Thymus* 54. *Thymus* 55. *Thymus* 56. *Thymus* 57. *Thymus* 58. *Thymus* 59. *Thymus* 60. *Thymus* 61. *Thymus* 62. *Thymus* 63. *Thymus* 64. *Thymus* 65. *Thymus* 66. *Thymus* 67. *Thymus* 68. *Thymus* 69. *Thymus* 70. *Thymus* 71. *Thymus* 72. *Thymus* 73. *Thymus* 74. *Thymus* 75. *Thymus* 76. *Thymus* 77. *Thymus* 78. *Thymus* 79. *Thymus* 80. *Thymus* 81. *Thymus* 82. *Thymus* 83. *Thymus* 84. *Thymus* 85. *Thymus* 86. *Thymus* 87. *Thymus* 88. *Thymus* 89. *Thymus* 90. *Thymus* 91. *Thymus* 92. *Thymus* 93. *Thymus* 94. *Thymus* 95. *Thymus* 96. *Thymus* 97. *Thymus* 98. *Thymus* 99. *Thymus* 100. *Thymus*

TABLE IV
NOZZLE CHARACTERISTICS

A_t = Cross-sectional Area at Throat
 A_e = Cross-sectional Area at Exit
 r_t = Theoretical Ratio of Exit Pressure to Inlet Pressure
 r_a = Actual Ratio of Exit Pressure to Inlet Pressure
 M_t = Theoretical Mach Number at Exit (Frictionless Flow)
 M_a = Actual Mach Number at Exit
 C_v = Assumed Velocity Coefficient
 w = Flow in Pounds per Second
 G = Flow per Unit Area at Exit, Pounds per Squarefoot per Second
 T_1 = Inlet Temperature, Degrees F.
 P_1 = Inlet Pressure, Atmospheres

<u>NOTATION</u>	<u>NOZZLE # 1</u>	<u>NOZZLE # 2</u>	<u>NOZZLE # 3</u>
A_t/A_e	1.9307	1.2870	1.9307
r_t	.1000	.2200	.1000
r_a	.1240	.2750	.1833
M_t	2.1520	1.6180	2.1520
M_a	1.8500	1.3900	1.3900
C_v	.95	.95	
P_1	1.0000	.6667	1.0000
T_1	85	85	85
w	.0676	.0676	.0676
G	25.2000	25.2000	25.2000

1. The first of these is the fact that the system is not a simple one, but a complex one, involving many different factors, and the results of which are not always predictable.

<u>C. & SUMMER</u>	<u>C. & SUMMER</u>	<u>C. & SUMMER</u>	<u>REMARKS</u>
7000, I	0100, I	7000, I	2000, I
0000, I	0000, I	0000, I	2000, I
0100, I	0100, I	0100, I	2000, I
0200, I	0200, I	0200, I	2000, I
0300, I	0300, I	0300, I	2000, I
	0400, I		2000, I
0500, I	0500, I	0500, I	2000, I
	0600, I		2000, I
0700, I	0700, I	0700, I	2000, I
0800, I	0800, I	0800, I	2000, I
0900, I	0900, I	0900, I	2000, I
1000, I	1000, I	1000, I	2000, I
1100, I	1100, I	1100, I	2000, I
1200, I	1200, I	1200, I	2000, I
1300, I	1300, I	1300, I	2000, I
1400, I	1400, I	1400, I	2000, I
1500, I	1500, I	1500, I	2000, I
1600, I	1600, I	1600, I	2000, I
1700, I	1700, I	1700, I	2000, I
1800, I	1800, I	1800, I	2000, I
1900, I	1900, I	1900, I	2000, I
2000, I	2000, I	2000, I	2000, I

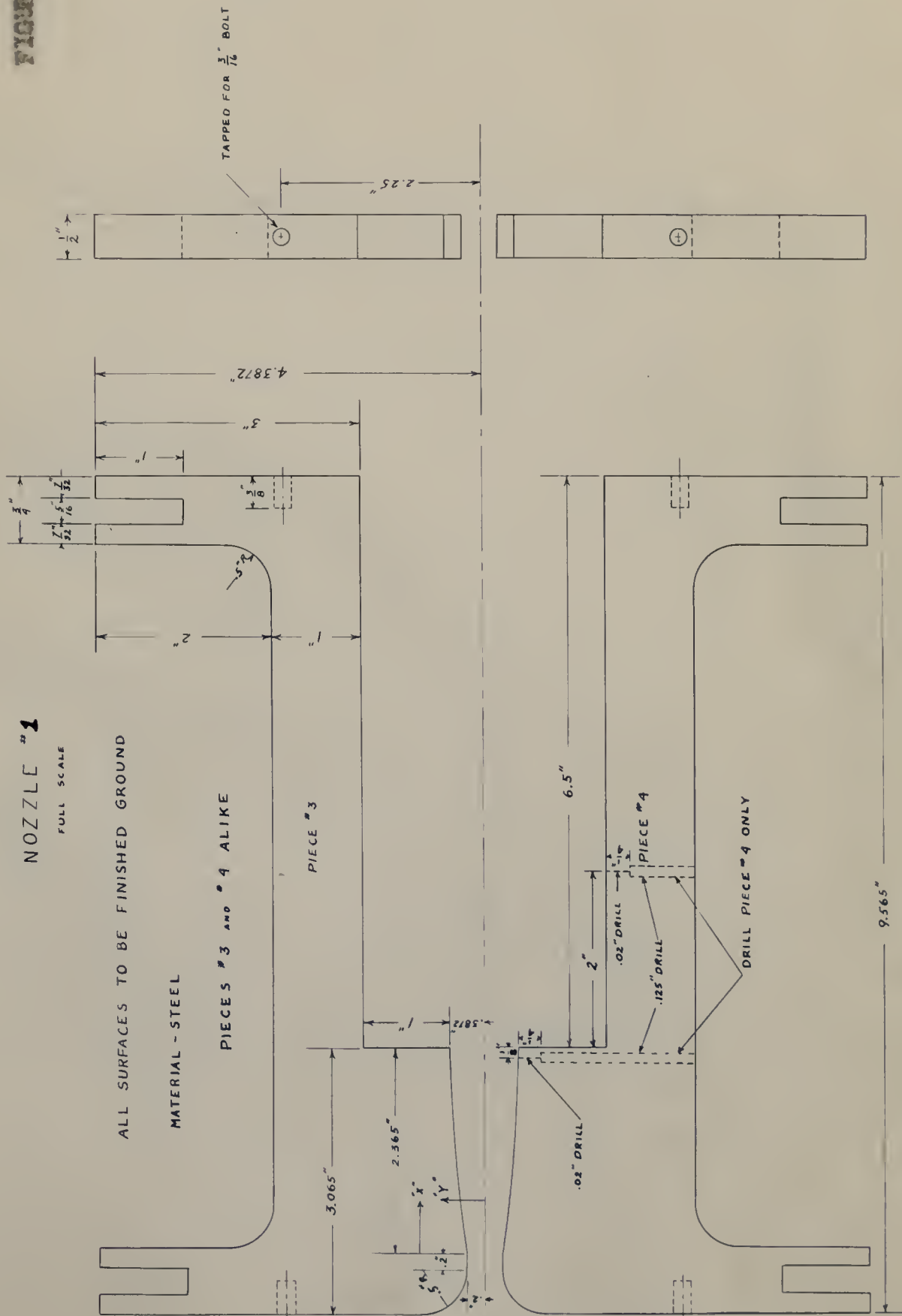
FIGURE XXXI

NOZZLE #1
FULL SCALE

ALL SURFACES TO BE FINISHED GROUND

MATERIAL - STEEL

PIECES #3 AND #4 ALIKE



OFFSETS NOZZLE #1

"X"	"Y"
0	.2000
.87	.3100
.95	.3200
1.00	.3250
1.10	.3360
1.20	.3470
1.30	.3550
1.40	.3635
1.50	.3690
1.60	.3740
1.70	.3790
1.80	.3830
1.90	.3850
2.00	.3860
2.10	.3865
2.20	.3870
2.24	.3872
2.365	.3872

STRAIGHT SLOPE

CURVED PORT

ST. HORIZ. PORT: 0

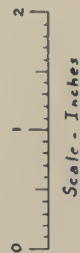
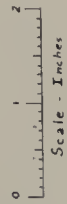


FIGURE XXVII

OFFSETS NOZZLE 2

	X"	Y"
STRAIGHT SLOPING	0	.3000
	1.00	.3500
	1.20	.3520
	1.30	.3600
	1.40	.3675
CURVED PORTION	1.50	.3710
	1.60	.3742
	1.70	.3775
	1.80	.3800
	1.90	.3825
ST. HORIZ. PORTION	2.00	.3850
	2.10	.3860
	2.20	.3870
	2.24	.3872
	2.365	.3872



NOZZLE #2
FULL SCALE

ALL SURFACES TO BE FINISHED GRIND
MATERIAL - STEEL

PIECES #5 AND #6 ALIKE

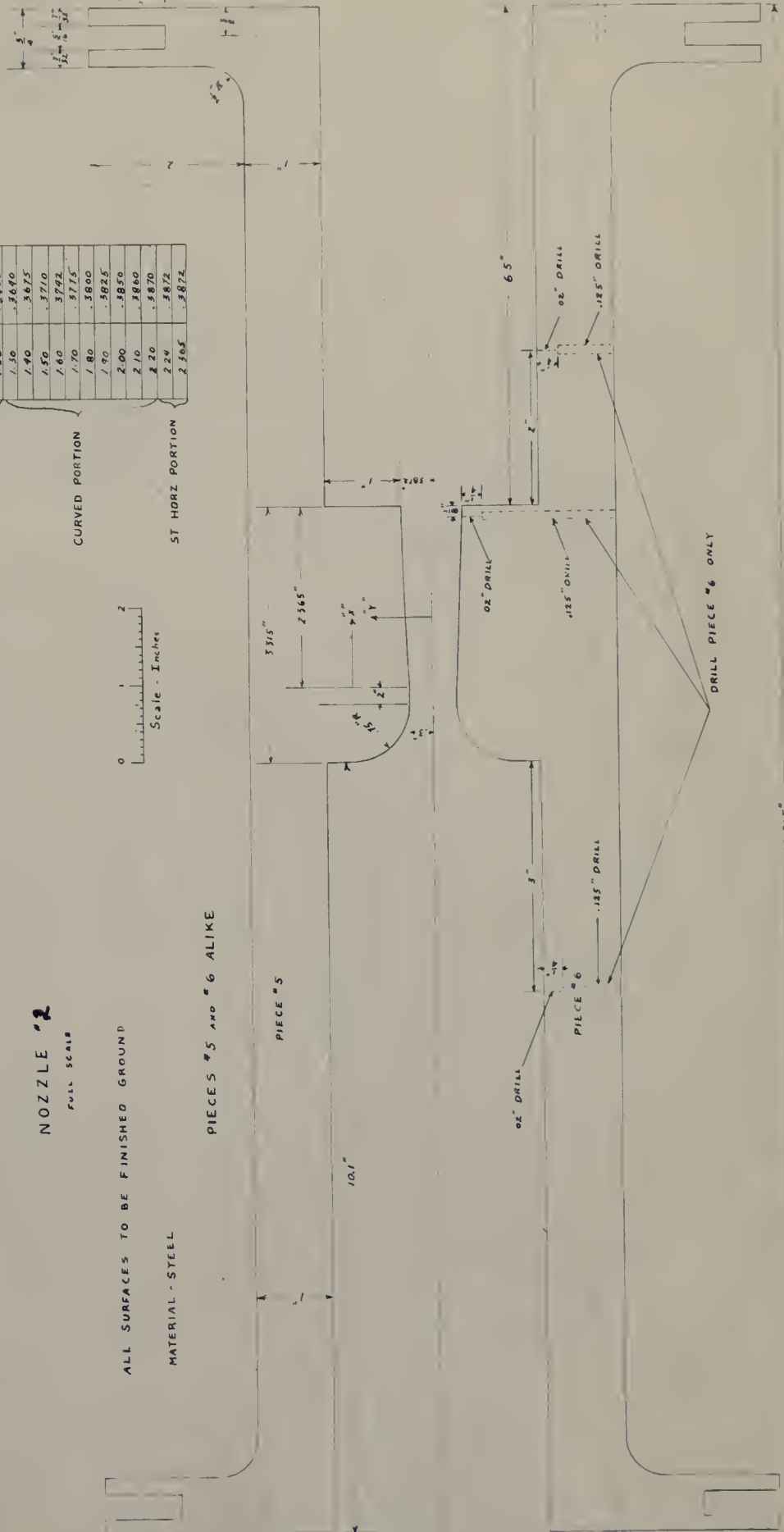


FIGURE XXVIII

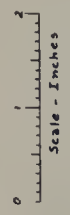
OFFSETS NOZZLE "3"

"X" "Y"		STRAIGHT SLOPING
"X"	"Y"	
0	.2000	STRAIGHT SLOPING
.87	.3100	
.95	.3200	
1.00	.3250	
1.10	.3300	
1.20	.3350	
1.30	.3400	
1.40	.3450	
1.50	.3500	
1.60	.3550	
1.70	.3600	CURVED PORTION
1.80	.3650	
1.90	.3700	
2.00	.3750	
2.10	.3800	
2.20	.3850	
2.30	.3900	
2.40	.3950	
2.50	.4000	
2.60	.4050	ST. HORIZ. PORTION
2.70	.4100	

NOZZLE "3" FULL SCALE

ALL SURFACES TO BE FINISHED GRIND

MATERIAL - STEEL



PIECES "1" AND "2" ALIKE

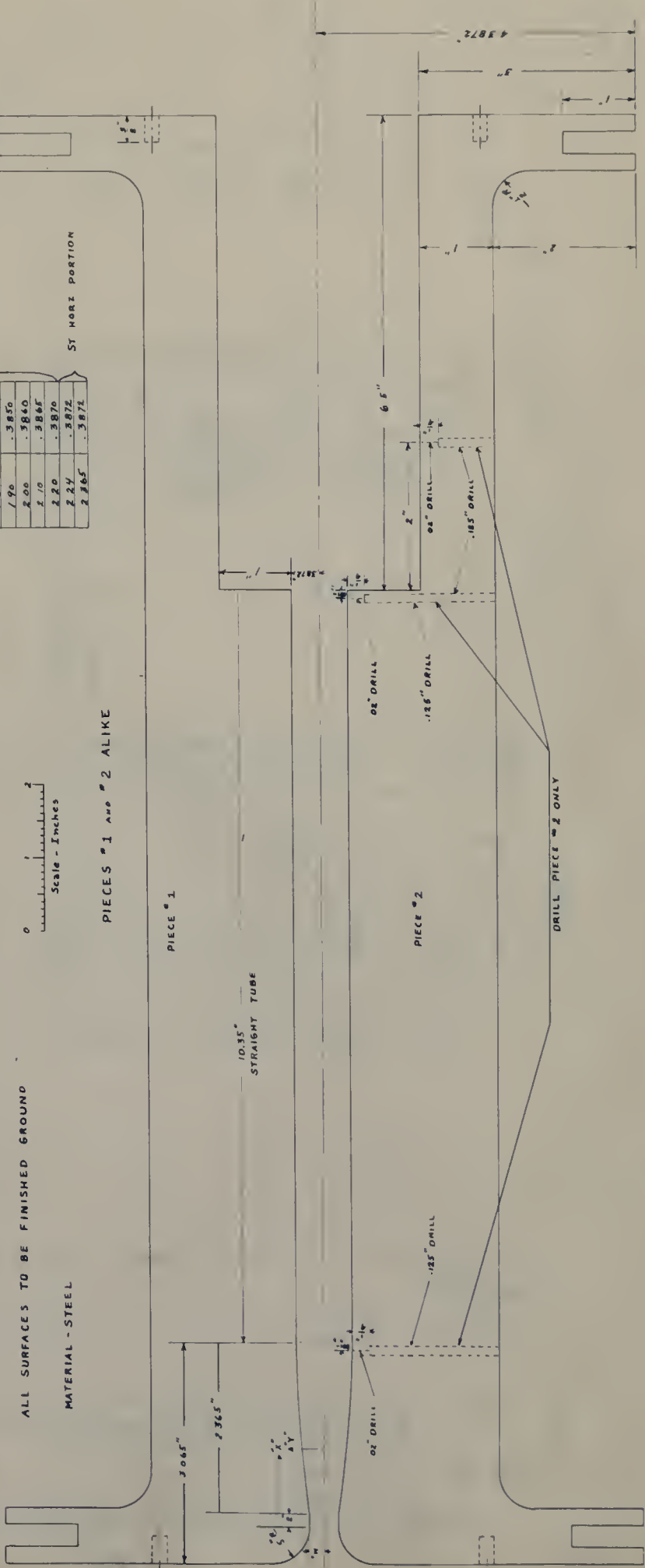
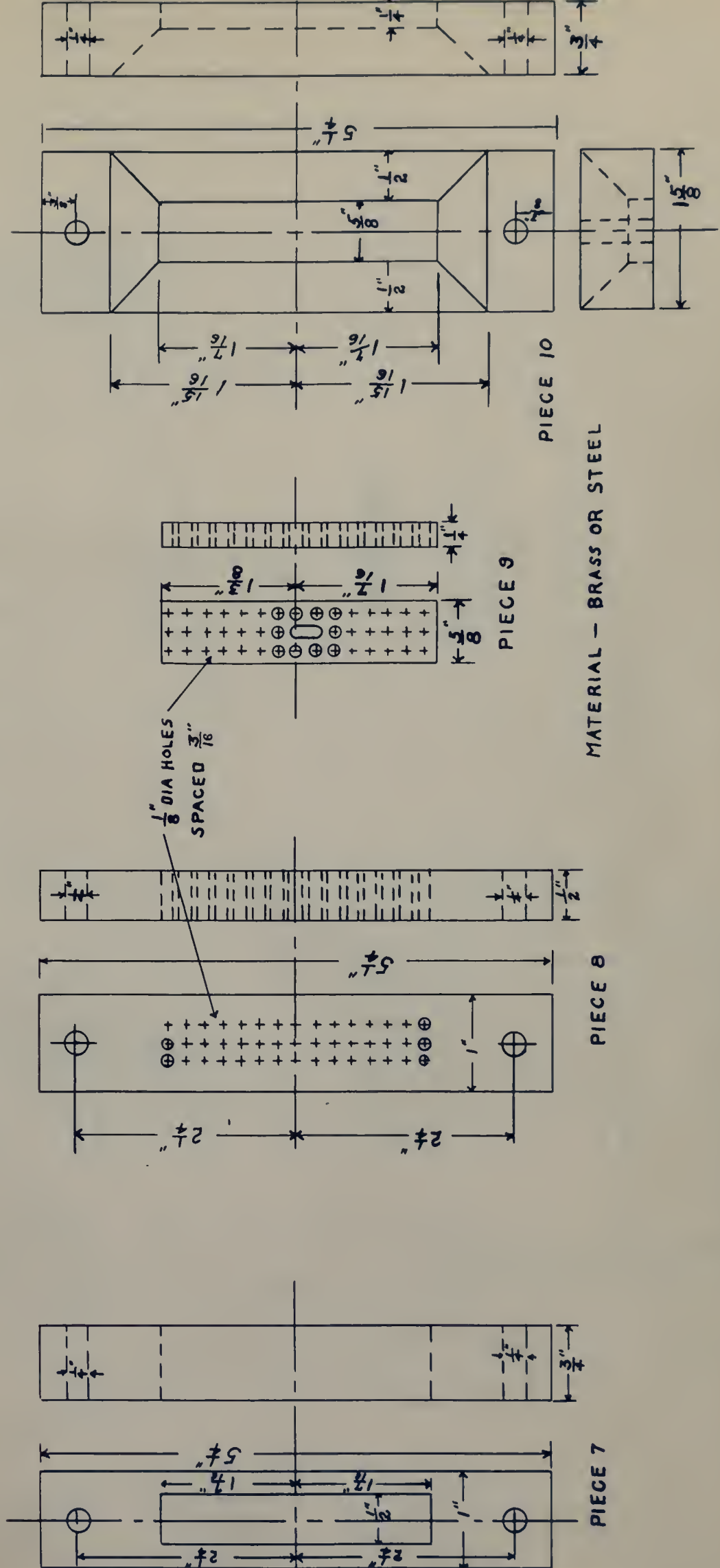


FIGURE XXXIX
REDUCING FITTING



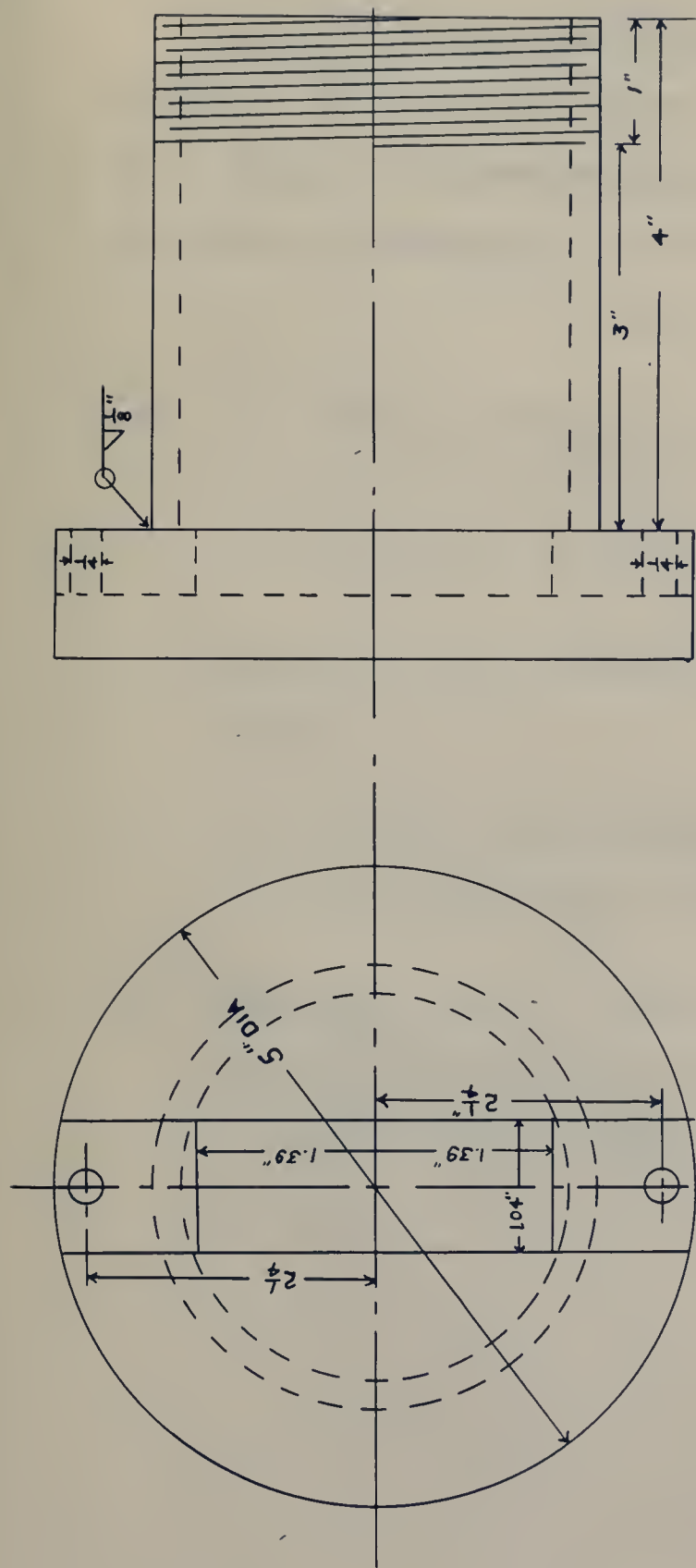
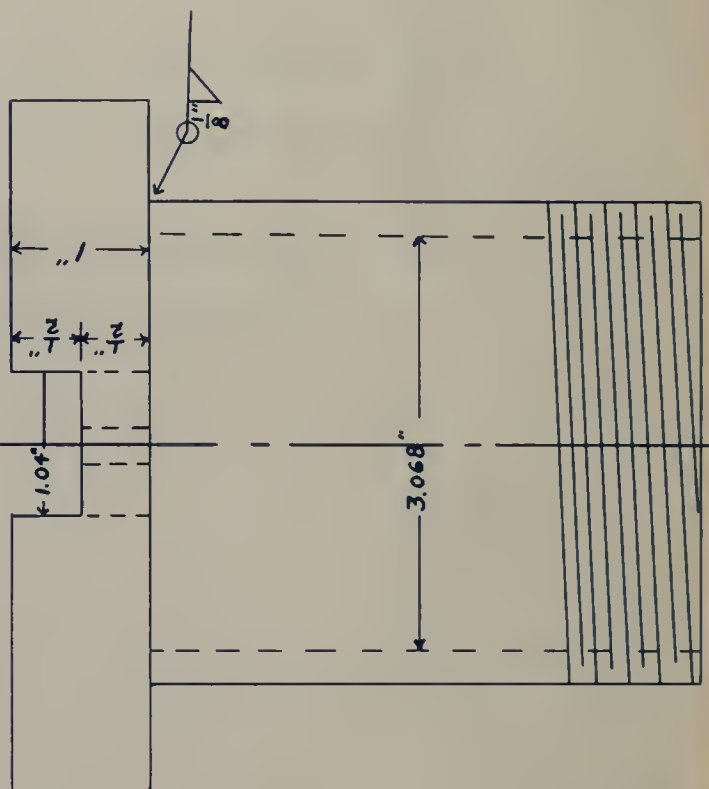
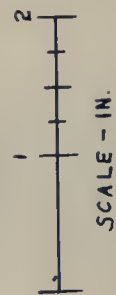


FIGURE XXX

EXHAUST FITTING
MATERIAL-STEEL



APPENDIX C -- LOCATION OF ORIGINAL DATA

All of the original nozzle design calculations, photographic negatives, and the nozzle profiles are in the possession of Mr. E. P. Neumann of the Mechanical Engineering Department, Massachusetts Institute of Technology.

All of the original maps, aerial photographs, photographs, and the aerial profiles are in the possession of Mr. E. P. Newman of the Mechanical Engineering Department, Massachusetts Institute of Technology.

APPENDIX D -- BIBLIOGRAPHY

1. L.A. DeFrate, "Investigation of Supersonic Flow in Nozzles and Tubes by the Schlieren Method", Master's Thesis, M.I.T., 1943.
2. Lieut. F.M. Huron, U.S.N., and Lieut. M.P. Nelson, U.S.N., "Investigation of Supersonic Flow in Nozzles and Tubes", Master's Thesis, M.I.T., 1944.
3. Lt. Comdr. J.W. Dolan, Jr., U.S.N. and Lt. Comdr. R.V. Laney, U.S.N., "Experimental Study of Supersonic Flow in the Prandtl Nozzle", Master's Thesis, M.I.T., 1944.
4. Joseph H. Keenan, Thermodynamics, John Wiley and Sons, New York, 1941.
5. Dr. A. Stodola, Steam and Gas Turbines, Vol. II, translated by Dr. Louis C. Lowenstein, McGraw Hill Book Co., Inc., New York.
6. J.H. Keenan and E.P. Neumann, "Friction in Pipes at Supersonic and Subsonic Velocities", National Advisory Committee for Aeronautics, Technical Note # 963.

1. L.A. Hyatt, "Investigation of Subnormal Flow in Sewers and Pipes to the Sewerage System", Master's Thesis, M.I.T., 1947.
2. L.A. Hyatt, "Investigation of Subnormal Flow in Sewers and Pipes", Master's Thesis, M.I.T., 1947.
3. L.A. Hyatt, "Investigation of Subnormal Flow in Sewers and Pipes", Master's Thesis, M.I.T., 1947.
4. L.A. Hyatt, "Investigation of Subnormal Flow in Sewers and Pipes", Master's Thesis, M.I.T., 1947.
5. L.A. Hyatt, "Investigation of Subnormal Flow in Sewers and Pipes", Master's Thesis, M.I.T., 1947.
6. L.A. Hyatt, "Investigation of Subnormal Flow in Sewers and Pipes", Master's Thesis, M.I.T., 1947.
7. L.A. Hyatt, "Investigation of Subnormal Flow in Sewers and Pipes", Master's Thesis, M.I.T., 1947.
8. L.A. Hyatt, "Investigation of Subnormal Flow in Sewers and Pipes", Master's Thesis, M.I.T., 1947.
9. L.A. Hyatt, "Investigation of Subnormal Flow in Sewers and Pipes", Master's Thesis, M.I.T., 1947.
10. L.A. Hyatt, "Investigation of Subnormal Flow in Sewers and Pipes", Master's Thesis, M.I.T., 1947.

DATA DUM

AUG 31
AP 26 62
FE 17 64
3 NOV 68

BINDERY
11932
12942
18289

Thesis
P34

Perry

Schlieren observation of
supersonic discharge.

11660

★
AP 26 62
FE 17 64
3 NOV 63
3 NOV 68

BINDERY
11932
12942
18289
18289

Thesis

11660

P34 Perry

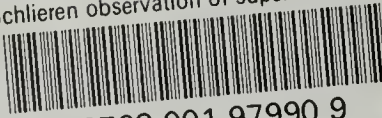
Schlieren observation of super-
sonic discharge.

Library
U. S. Naval Postgraduate School
Monterey, California



thesP34

Schlieren observation of supersonic disc



3 2768 001 97990 9

DUDLEY KNOX LIBRARY